II. "Note on a preliminary Comparison between the Dates of Cyclonic Storms in Great Britain and those of Magnetic Disturbances at the Kew Observatory." By BALFOUR STEWART, M.A., LL.D., F.R.S., and WM. LANT CARPENTER, B.A., B.Sc. Received February 11, 1885.

We took the dates of thirty storms from Mr. Scott's paper entitled "The Equinoctial Gales; do they occur in the British Isles?" in the "Quarterly Journal of the Meteorological Society" for October, 1884, and by the kindness of Mr. Whipple, of the Kew Observatory, were enabled to make the comparison mentioned above.

Out of these thirty storms, in twenty-three cases there is a distinct magnetic disturbance, for the most part preceding the storm by somewhat more than a day. We do not, however, imagine that we have thus proved the fact of such a connexion, but think the results we have attained sufficient to justify us in pursuing the subject.

February 26, 1885.

THE TREASURER in the Chair.

The Presents received were laid on the table and thanks ordered for them.

The following Papers were read:—

I. "On a remarkable Phenomenon of Crystalline Reflection." By G. G. STOKES, M.A., Sec. R.S., Lucasian Professor of Mathematics in the University of Cambridge. Received February 25, 1885.

Introduction.

In a letter to me, dated March 29, 1854, the late Dr. W. Bird Herapath enclosed for me some iridescent crystals of chlorate of potash, which he thought were worth my examination. He noticed the intense brilliancy of the colour of the reflected light, the change of tint with the angle of incidence, and the apparent absence of polarisation in the colour seen by reflection.

The crystals were thin and fragile, and rather small. I did not see how the colour was produced, but I took for granted that it must be

by some internal reflection, or possibly oblique refraction, at the surfaces of the crystalline plates that the light was polarised and analysed, being modified between polarisation and analysation by passage across the crystalline plate, the normal to which I supposed must be sufficiently near to one of the optic axes to allow colours to be shown, which would require no great proximity, as the plates were very thin. To make out precisely how the colours were produced seemed to promise a very troublesome investigation on account of the thinness and smallness of the crystals: and supposing that the issue of the investigation would be merely to show in what precise way the phenomenon was brought about by the operation of well-known causes, I did not feel disposed to engage in it, and so the matter dropped.

But more than a year ago Professor E. J. Mills, F.R.S., was so good as to send me a fine collection of splendidly coloured crystals of the salt of considerable size, several of the plates having an area of a square inch or more, and all of them being thick enough to handle without difficulty. In the course of his letter mentioning the despatch of the crystals, Professor Mills writes: "They (the coloured crystals) are, I am told, very pure chemically, containing at most 0·1 per cent. foreign matter. They are rarely observed—one or two perhaps now and then, in a large crystallisation . . . . . I have several times noticed that small potassic chlorate crystals, when rapidly forming from a strong solution, show what I suppose to be interference colours; but the fully formed crystals do not show them."

Some time later I was put into communication with Mr. Stanford, of the North British Chemical Works, Glasgow, from which establishment the crystals sent me by Professor Mills had come. Mr. Stanford obligingly sent me a further supply of these interesting crystals, and was so kind as to offer to try any experiment that I might suggest as to their formation.

I am informed that at the recent Health Exhibition a stand was exhibited from the chemical works at Widnes, showing a fine collection of brilliantly coloured crystals of chlorate of potash. I did not see it. It would seem that the existence of these coloured crystals is pretty generally known, but I have not seen mention of them in any scientific journal, nor, so far as I know, has the subject been investigated.

On viewing through a direct-vision spectroscope the colours of the crystals which I had just received from Professor Mills, the first glance at the spectrum showed me that there must be something very strange and unusual about the phenomenon, and determined me to endeavour to make out the cause of the production of these colours. The result of my examination is described in the present paper.

SECTION I.—*Preliminary Physical Examination.*

1. It will be necessary to premise that chlorate of potash belongs to the oblique system of crystallisation. The fundamental form may be taken as an oblique prism on a rhombic base, the plane bisecting the obtuse dihedral angle of the prism being the plane of symmetry. Rammelsberg denotes the sides of the prism by P, and the base by C, and gives for the inclinations of the faces PP=104° 22′ and CP=105° 35′. The face C, which is perpendicular to the plane of symmetry, is so placed as to bring three obtuse plane angles together at two opposite corners of the parallelopiped. The salt usually forms flat rhombic or hexagonal plates parallel to the C plane, the edges of the rhombus being parallel to the intersections of the P faces by the C plane, and the hexagons being formed from the rhombic plates by truncating the acute angles by faces parallel to the intersection of the C plane by the plane of symmetry.

The plane angles of the rhombic plates, calculated from the numbers given by Rammelsberg, are 100° 56′ and 79° 4′, while the hexagonal plates present end-angles of 100° 56′ and four side-angles of 129° 32′. These angles are sufficiently different to allow in most cases the principal plane of a plate, or even of a fragment of a plate, to be determined at once by inspection. But in any case of doubt it may readily be found without breaking the crystal by examining it in polarised light. There are good cleavages parallel to the two P planes and to the C plane. The crystals are very commonly twinned, the twin plane being C.

2. If one of the brilliantly coloured crystals be examined by reflection, and turned round in its own plane, without altering the angle of incidence, the colour disappears twice in a complete revolution. The vanishing positions are those in which the plane of incidence is the plane of symmetry. The colour is perhaps most vivid in a perpendicular plane; but for a very considerable change of azimuth from the perpendicular plane there is little variation in the intensity of the colour. There is no perceptible change of tint, but on approaching the plane of symmetry the colour gets more and more drowned in the white light reflected from the surface.

3. If instead of altering the azimuth of the plane of incidence a plane be chosen which gives vivid colour, and the angle of incidence be altered, the colour changes very materially. If we begin with a small angle the colour begins to appear while the angle of incidence is still quite moderate. What the initial colour is, varies from one crystal to another. As we increase the angle of incidence the colour becomes vivid, at the same time changing, and as we continue to increase the angle the change of colour goes on. The change is always in the order of increasing refrangibility; for example, from

red through green to blue. Not unfrequently, however, the initial tint may be green or blue, and on approaching a grazing incidence we may get red or even yellow mixed with the blue, as if a second order of colours were commencing.

4. The colours are not in any way due to absorption; the transmitted light is strictly complementary to the reflected, and whatever is missing in the reflected is found in the transmitted. As in the case of Newton's rings, the reflected tints are much more vivid than the transmitted, though, as will presently appear, for a very different reason.

5. As Dr. Herapath remarked to me long ago, the coloured light is not polarised. It is produced indifferently whether the incident light be common light or light polarised in any plane, and is seen whether the reflected light be viewed directly or through a Nicol's prism turned in any way. The only difference appears to be that if the incident light be polarised, or the reflected light analysed, so as to furnish or retain light polarised perpendicularly to the plane of incidence, the white light reflected from the surface, which to a certain extent masks the coloured light, is more or less got rid of.

6. The character of the spectrum of the reflected light is most remarkable, and was wholly unexpected. A direct-vision hand spectroscope was used in the observations, and the crystal was generally examined in a direction roughly perpendicular to the plane of symmetry; but it is shown well through a wide range of azimuth of the plane of incidence. No two crystals, we may say, are alike as to the spectrum which they show, but there are certain features common to all. The remarkable feature is that there is a pretty narrow band, or it may be a limited portion of the spectrum, but still in general of no great extent, where the light suffers total or all but total reflection. As the angle of incidence is increased, these bands move rapidly in the direction of increasing refrangibility, at the same time increasing in width. The character of the spectrum gradually changes as the angle of incidence is increased; for example, a single band may divide into two or three bands.

The bands are most sharply defined at a moderate angle of incidence. When the angle of incidence is considerably increased, the bands usually get somewhat vague, at least towards the edges.

7. The commonest kind of spectrum, especially in crystals prepared on a small scale, which will be mentioned presently, is one showing only a single bright band; and I will describe at greater length the phenomena presented in this case.

When the angle of incidence is very small, the light reflected from the reflecting surfaces of the crystal shows only a continuous spectrum. As the angle of incidence is increased, while it is still quite moderate a very narrow bright band shows itself in some part

of the spectrum. The particular part varies from one crystal to another; it may be anywhere from the extreme red to the extreme violet. It stands out by its greatly superior brightness on the general ground of the continuous spectrum, and when it is fully formed the reflection over the greater part of it appears to be total. The appearance recalls that of a bright band such as the green band seen when a calcium salt, or the orange band seen when a strontium salt, is put into a Bunsen flame. The bright band is frequently accompanied right and left by maxima and minima of illumination, forming bands of altogether subordinate importance as regards their illumination. Sometimes these seem to be absent, and I cannot say whether they are an essential feature of the phenomenon, which sometimes fail to be seen because the structure on which the bands depend is not quite regularly formed, or whether, on the other hand, they are something depending on a different cause.

Disregarding these altogether subordinate bands, and taking account of the mean illumination, it seems as if the brightness of the spectrum for a little way right and left of the bright band were somewhat less than that at a greater distance.

When the main band occurs at either of the faint ends of the spectrum, it is visible, by its superior brightness, in a region which, as regards the continuous spectrum, is too faint to be seen, and thus it appears separated from the continuous spectrum by a dark interval.

When the angle of incidence is increased, the band moves in the direction of increasing refrangibility, and at the same time increases rapidly in breadth. The increase of breadth is far too rapid to be accounted for merely as the result of a different law of separation of the colours, which in a diffraction spectrum would be separated approximately according to the squared reciprocal of the wave-length, while in bands depending on direct interference the phase of illumination would change according to the wave-length.

8. The transmitted light being complementary to the incident, we have a dark band in the transmitted answering to the bright band in the reflected. In those crystals in which the band is best formed, it appears as a narrow black band even in bright light. When the band first appears as we recede from a normal incidence it is extremely narrow, but it rapidly increases in breadth as the angle of incidence is increased.

9. Some of the general features of the phenomenon were prettily shown in the following experiment:—

Choosing a crystal in which the bright band in the reflected light began to appear, as the incidence was increased, on the red side of the line D, so that on continuing to increase the incidence it passed through the place of the line D before it had become of any great

width, I viewed through the crystal a sheet of white paper illuminated by a soda flame. A dark ring was seen on the paper, which was circular, or nearly so, and was interrupted in two places at opposite extremities of a diameter, namely, the places where the ring was cut by the plane of symmetry. The light of the refrangibility of D was so nearly excluded from the greater part of the ring that it appeared nearly black, though slightly bluish, as it was illuminated by the feeble radiation from the flame belonging to refrangibilities other than those of the immediate neighbourhood of D. The ends of the two halves of the ring became feeble as they approached the plane of symmetry. A subordinate comparatively faint ring lay in this crystal immediately outside the main one.

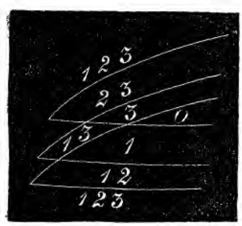
10. Suspecting that the production of colour was in some way connected with twinning, I examined the cleft edge of some of the crystals which happened to have been broken across, and found that the bright reflection given by the exposed surface was interrupted by a line, much finer than a hair, running parallel to the C faces, which could be easily seen with a watchmaker's lens, if not with the naked eye. This line was dark on the illuminated bright surface exposed by cleavage, a surface which I suppose illuminated by a source of light not too large, such as a lamp, or a window at some distance. The plane of incidence being supposed normal to the intersection of the cleavage plane by the C faces, on turning the crystal in a proper direction round a normal to the plane of incidence, the light ceased to be reflected from the cleavage surface, and after turning through a certain angle, the narrow line, which previously had been dark, was seen to glisten, indicating the existence of a reflecting surface, though it was much too narrow to get a reflected image from off it. The direction of rotation required to make the fine line glisten was what it ought to be on the supposition that the fine line was the cleavage face of an extremely narrow twin stratum.

11. On examining the fine line under the microscope, it was found to be of different thicknesses in different crystals, though in those crystals which showed colour it did not vary very greatly. On putting a little lycopodium on the cleavage face interrupted by the fine line, it was seen that in those crystals which showed colour the breadth of the twin stratum varied from a little greater to a little less than the breadth of a spore. The thickness accordingly ranged somewhere about the thousandth of an inch, such being the diameter of the spores. The stratum was visibly thicker in those crystals which showed their bright band in the red than in those which showed it in the blue.

12. That the thin twin stratum was in fact the seat of the colour, admitted of being proved by a very simple experiment. It was sufficient to hold a needle, or the blade of a penknife (I will suppose the

latter), close to or touching the surface of the crystal while it was illuminated by light coming approximately in one direction, suppose from a lamp, or from a window a little way off, and to examine the shadows with a watchmaker's lens. The light reflected from the crystal comes partly from the upper surface, partly from the twin stratum, partly from the under surface, which, however, may be too irregular to give a good reflection. The twin stratum is much too thin to allow of separating the light reflected from its two surfaces in an observation like the present, and it must therefore be spoken of as simply a reflecting surface.

Corresponding to the three reflecting surfaces are three shadows, where the incident light is cut off: (1) from the upper surface, (2) from the twin stratum, (3) from the under surface. Where the body casting the shadow is pretty broad in one part, as the blade of a penknife, the shadows in part overlap. The shadows are arranged as in the figure, where the numerals mark the streams of light reflected from the portions of the field on which they are respectively written, 1 denoting the stream reflected from the upper surface, 2, that reflected from the twin stratum, 3, that reflected from the under surface.



Let the crystal show by reflection, at the incidence at which the observation is made, say a green colour. Then this green colour is seen in the full field 123, though mixed with the white light reflected from the upper surface. The green is a good deal more vivid in the field 23, as the reflection from the upper surface is got rid of. The green is wholly absent from the fields 3, 0, 13, and 1. The field 3, and perhaps also the field 13, may show a little of the complementary red from transmitted light. The distinction between the fields 12 and 123 is not conspicuous, and often cannot be made out. The distinction, so far as it depends on the third shadow, is strongest between 3 and 0, and next to that between 13 and 1. We are not obliged, however, to have recourse to the third shadow, which is often difficult to see; the first two are amply sufficient.

Suppose we take a crystal which is broken at the edge so as to expose a cleavage surface interrupted by the cleavage of the narrow

twin stratum. The stratum usually lies a good deal nearer to one C face than the other. Now when the two faces are turned uppermost alternately, and the distances between the first and second shadows are observed, they are found to be, as nearly as can be estimated, in the same proportion as the distances from the twin stratum to the two faces respectively.

Again, one of the crystals showed the exposed section of the twin stratum slightly inclined to one of the broad faces, which though smooth to the touch did not give a perfect reflection of objects viewed in it. On holding different parts of the blade of a penknife opposite to different parts of this face, the distance between the first and second shadows was found to vary, as nearly as could be guessed, in proportion to the thickness of crystal between the upper face and the twin stratum.

The conclusion was confirmed by observations made with sunlight; but the simple method of shadows is quite as good, and even by itself perfectly satisfactory.

13. Another useful method of observation, not so very simple as the last, is the following. A slit, suppose horizontal, not very narrow, is placed in front of the flame of a lamp at some distance, and an image of the slit is formed by a suitable lens, such as the compound achromatic objective of an opera-glass. The crystal is placed so as to receive in focus the image of the slit, being inclined at a suitable angle, usually in a plane perpendicular to the plane of symmetry. The eye is held in a position to catch the reflected light, and the images formed by the different reflections are viewed through a watch-maker's lens. If the slit be not too broad, the images formed by reflection from the upper surface, from the twin stratum, and from the under surface are seen distinct from each other, so that the light reflected from the twin stratum may be studied apart from that reflected from the upper and under surfaces.

In this mode of observation it can readily be seen, by turning the crystal in its own plane, and noticing the middle image, which is that reflected from the twin stratum, how very small a rotation out of the position in which the plane of incidence had been the plane of symmetry suffices to re-introduce the coloured light, which had vanished in that critical position, which appears to be a position not merely of absence of colour, but of absence of light altogether; at least if there be any it is too feeble to be seen in this mode of observation, though from theoretical considerations we should conclude that there must be a very little reflected light, polarised perpendicularly to the plane of incidence.

14. On allowing a strong solution of chlorate of potash in hot water to crystallise rapidly, in which case excessively thin plates are formed in the bosom of the liquid, I noticed the play of colours by

reflection mentioned by Professor Mills as belonging to the crystals in general at an early stage of their growth. This, however, proved to be quite a different and no doubt a much simpler phenomenon. The difference was shown by the polarisation of the light, and above all by the character of the spectrum of the light so reflected, which resembled ordinary spectra of interference, and did not present the remarkable character of the spectra of the peculiar crystals.

15. When, however, the whole was left to itself for a day or so, among the mass of usually colourless crystals a few were found here and there which showed brilliant colours. These colours were commonly far more brilliant than those of the crystals mentioned in the preceding paragraph, and they showed to perfection the distinctive character of the spectrum of the peculiar crystals. It would have been very troublesome, if possible at all, to examine the twinning of such thin and tender plates as those thus obtained by working on a small scale; but the character of the spectrum, which is perhaps the most remarkable feature of the phenomenon, as well as the dependence of the colour on the orientation, may be examined very well; and thus anyone can study *these* features of the phenomenon, though he may not have access to such fine coloured crystals as those sent me by Professor Mills.

16. A certain amount of disturbance during the early stages of crystallisation, whether from natural currents of convection or from purposely stirring the solution somewhat gently so as not to break the crystals, seems favourable to the production of the peculiar crystals. When the salt crystallised slowly from a quiet solution I did not obtain them.

17. As it is easy in this way, by picking out the peculiar crystals from several crystallisations, to obtain a good number of them, the observer may satisfy himself as to the most usual character of the spectrum. It is best studied at a moderate incidence, as it is sharper than when the incidence is considerable. The spectrum most commonly shows a single intensely bright band, standing out on the general ground of a continuous spectrum of moderate intensity.

A few cases seem worthy of special mention. In one instance two bright bands were seen, one at each faint end of the spectrum, somewhat recalling the flame-spectrum of potassium salts. In another case a red, a green, and a blue band were seen, reminding one of the spectrum of incandescent hydrogen. This crystal in air was nearly colourless at moderate incidences, but showed red at rather high incidences. In another case the crystal was red of intense brilliancy in the mother-liquor, but was colourless when taken out, even at high incidences. Presumably the stratum in this case was so thick that a steeper incidence than could be obtained out of air was required to develop colour.

18. The number of coloured crystals obtained by crystallisations on a small scale, though very small, it is true, compared with the number of colourless ones, was still so much larger than Professor Mills's description of the rarity of the crystals had led me to expect, that I at one time doubted whether the simply twinned crystals which are so very common, if taken at a period of their growth when one component is still very thin, and of suitable thickness, might not possibly show the phenomenon, though the thin twin was in contact on one face only with the brother twin, the other face being in the mother-liquor or in air. The circumstances of reflection and transmission at the first surface of the twin plate must be very different according as it is in contact with the brother crystal, or else with the mother-liquor, or air, or some other fluid; and yet the peculiar spectrum was shown all the same whether the crystal was in air, or immersed in the mother-liquor, or in rock oil. However, to make sure of the matter I took a simply twinned crystal, and ground it at a slight inclination to the C face till the twin plane was partly ground away, thus leaving a very slender twin wedge forming part of the compound crystal, and polished the ground surface. On examining the reflected light with a lens, no colour was seen about the edge of the wedge, where the thickness of the wedge tapered away to nothing; and that, although the bands seen near the edge in polarised light, which was subsequently analysed, showed that had colours been producible in this way as they are by a thin twin stratum, they would not have been too narrow to escape observation.

In another experiment a simply twinned crystal was hollowed out till the twin plane was nearly reached. The hollowing was then continued with the wetted finger, so as to leave a concave smooth surface, the crystal being examined at short intervals in polarised light as the work went on, so as to know when the twin plane was pierced. But though in this case the twin plane formed a secant plane, nearly a tangent plane, to the worked surface, and near the section the twin portion of the crystal must have been very thin for a breadth by no means infinitesimal, as was shown by examination in polarised light, yet no colours were seen by reflection. I conclude therefore that the production of these colours requires the twin stratum to be in contact on *both* its faces with the brother crystal.

19. The fact that a single bright band is what most usually presents itself in the spectrum of the reflected light (though sometimes two or three such bands at regular intervals may be seen) seems to warrant us to regard that as the kind of spectrum belonging to the simplest form of twin stratum, namely, one in which there are just the two twin surfaces near together. The more complicated spectra seem to point to a compound interference, and to be referable to the existence of more than two twin planes very near together; and in

fact in some of the crystals which showed the more complicated spectra, and which were broken across, I was able to make out under the microscope the existence of a system of more than two twin plans, close together. Restricting ourselves to what may be regarded as the normal case, we have then to inquire in what way the existence of two twin planes near together can account for the peculiar character of the spectrum of the reflected or transmitted light.

Section II.—*Of the Proximate Cause of the Phenomenon.*

20. Though I am not at present prepared to give a complete explanation of the very curious phenomenon I have described, I have thought it advisable to bring the subject before the Society, that the attention of others may be directed to it.

That the seat of the coloration is in a thin twin stratum, admits I think of no doubt whatsoever. A single twin plane does not show anything of the kind.

For the production of the colour the stratum must be neither too thick nor too thin. Twin strata a good deal thicker than those that show colour are common enough; and among the crystals sent to me I have found some twin strata which were a good deal thinner, in which case the crystal showed no colour.

The more complicated spectra which are frequently observed seem referable to the existence of more than two twin planes in close proximity. There is no reason to think that the explanation of these spectra would involve any new principle not already contained in the explanation of the appearance presented when there are only two twin planes, though the necessary formulæ would doubtless be more complicated.

Corresponding to a wave incident in any direction, in one component of a twin, on the twin plane, there are in general two refracted waves in the second component in planes slightly inclined to each other, and two reflected waves which also have their planes slightly inclined to each other, the angle of inclination, however, being by no means *very* small, as chlorate of potash is strongly double refracting. The planes of polarisation of the two refracted waves are approximately perpendicular to each other, as are also those of the two reflected waves; but on account of the different orientation of the two components of the twin, the planes of polarisation of the two refracted waves are in general altogether different from those of the incident wave and of its fellow, the trace of which on the twin plane would travel with the same velocity. In the plane of symmetry at any incidence, and for a small angle of incidence at any azimuth of the plane of incidence, the directions of the planes of polarisation of the two refracted waves agree accurately or nearly with those of the

incident wave and its fellow. In these cases, therefore, an incident wave would produce hardly more than one refracted wave, namely, that one which nearly agrees with the incident wave in direction of polarisation. In these cases the colours are not produced. It appears, therefore, that their production demands that the incident wave shall be very determinately divided into two refracted waves, accompanied of course by reflected waves.

It seems evident that the thickness of the stratum affects the result through the difference of phase which it entails in the two refracted waves on arriving at the second twin plane. But whereas in the ordinary case of the production of colour by the interposition of a crystalline plate between a polariser and an analyser, we are concerned only with the difference of retardation of the differently polarised pencils which are transmitted across the plate, and not with the absolute retardation, it is possible that in this case we must take into account not only the difference of retardation for the differently polarised pencils which traverse the stratum, but also the absolute retardation; that is, the retardation of the light reflected from the second relatively to that reflected from the first twin plane.

21. I have not up to the present seen my way to going further. It is certainly very extraordinary and paradoxical that light should suffer total or all but total reflection at a transparent stratum of the very same substance, merely differing in orientation, in which the light had been travelling, and that, independently of its polarisation. It can have nothing to do with ordinary total internal reflection, since it is observed at quite moderate incidences, and *only within very narrow limits* of the angle of incidence.